The Inelastic Scattering of Fast Neutrons

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In a previous communication[1] we have given the values of the energy levels and cross sections for the inelastic scattering of $2\frac{1}{2}$-Mev neutrons by fluorine, magnesium, and sulfur. The absolute γ-ray yield from the excited nuclei due to a known fast neutron flux was investigated with a pair of calibrated Geiger-Müller counters operated in coincidence. The energy of the γ-radiation was determined by the method of Bleuler and Zunti[2] from the absorption in aluminium of the secondary electrons produced by a polystyrene radiator. The absolute value of the neutron flux was measured with a proton recoil ionization chamber.[3] In this way the elements, beryllium, copper, chromium, and iron have also been investigated.

The method of Bleuler and Zunti permits the γ-ray energy to be found both from the form of the absorption curve and from the range of the secondary electrons. When the values of energy obtained in these two ways agree the γ-radiation is homogeneous, thus indicating the excitation of a single nuclear level only. Such homogeneity was found for the γ-radiation from chromium, magnesium, fluorine, and sulfur.

If the radiation is complex, agreement between the two values will not be obtained. However, the method of Bleuler and Zunti can be extended to the analysis of γ-ray spectra when two components are present. The high energy component is found from the range of the secondary electrons, and this value then enables the low energy component to be determined from the form of the absorption curve. Copper and iron both exhibited complex spectra.

Table I. Gamma-ray energies and inelastic scattering cross sections.

Element	γ-ray energy (Mev)	Inelastic scattering cross section
Beryllium	...	$<0.014\times10^{-24}$ cm²
Chromium	1.4 ± 0.1	1.2 ± 0.4
Copper	1.1 ± 0.1 2.2 ± 0.1	1.2 ± 0.6 0.34 ± 0.12
Fluorine	1.3 ± 0.1	0.52 ± 0.18
Iron	0.8 ± 0.1 2.2 ± 0.2	1.8 ± 1.3 0.14 ± 0.05
Magnesium	1.4 ± 0.1	0.75 ± 0.23
Sulfur	2.35 ± 0.15	0.38 ± 0.1

The copper spectrum could be resolved into two components: that of iron could be accounted for by two components but statistical uncertainty did not exclude the possible presence of γ-rays of intermediate energy. The analysis of the iron spectrum has been made on the basis of these two components. From considerations of the available energy it appears that these levels are separately excited.

The earlier results for fluorine, magnesium, and sulfur have been revised and are included in Table I. The cross sections given are for the naturally occurring elements.

[1] Beghian, Grace, Preston, and Halban, Phys. Rev. **77**, 286 (1950).
[2] E. Bleuler and W. Zunti, Helv. Phys. Acta **19**, 375 (1946).
[3] L. E. Beghian and H. Halban, Proc. Phys. Soc. (London) **62A**, 395 (1949).

On the Theory of Beta-Decay

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It has been found possible to write the matrix elements of standard beta-decay theory[1] in a way which not only gives the beta-spectra and angular distributions for arbitrary degree of forbiddenness, but also yields very simply the selection rules appropriate to any chosen type of interaction.

Table I. Degrees of forbiddenness f of transitions creating the system electron plus neutrino in states JSL. Even values of f refer to parity change no, odd values (underlined) to parity change yes. An * denotes that the term vanishes.

Dirac operators and values of S		$J=0$ $L=0, 1$	1 0, 1, 2	2 1, 2, 3	3 2, 3, 4	4 3, 4, 5
$1, \beta$	(0)	$0, \underline{*}$	$*, \underline{1}, *$	$*, 2, *$	$*, \underline{3}, *$	$*, 4, *$
$\boldsymbol{\alpha}, \beta\boldsymbol{\alpha}$	(1)	$\underline{*}, 2$	$\underline{1}, 2, \underline{3}$	$2, \underline{3}, 4$	$\underline{3}, 4, \underline{5}$	$4, 5, 6$
$\boldsymbol{\sigma}, \beta\boldsymbol{\sigma}$	(1)	$*, \underline{1}$	$0, \underline{1}, 2$	$\underline{1}, 2, \underline{3}$	$2, \underline{3}, 4$	$\underline{3}, 4, \underline{5}$
$\gamma_5, \beta\gamma_5$	(0)	$\underline{1}, *$	$*, 2, *$	$*, \underline{3}, *$	$*, 4, *$	$*, \underline{5}, *$

Thus, to anticipate, Table II enables the degree of forbiddenness of any emission with nuclear spin change $J_i\rightarrow J_f$ and parity change "yes" or "no" to be read off, for the three commonly used interactions.

States of the system $e+\nu$ (electron plus neutrino) are expressed as superpositions of wave functions $\psi(JM, j_e j_\nu)$ specified by the following quantities: total angular momentum J of the system as a whole, with z-component M, angular momentum j_e of the electron, angular momentum j_ν of the neutrino. J, of course, can have any integral value 0, 1, 2, etc. . . .

The magnitudes of the individual orbital angular momenta are not constants of the motion owing to relativistic effects. However an expansion of the form

$$\psi(JM, j_e j_\nu)=\sum_{L,S} A(L, S; j_e, j_\nu)\phi(JM, LS)$$

is possible, each term of which may be regarded as representing a state of the system $e+\nu$ having a definite total orbital angular momentum L and total spin $S=0$ or 1 ("spins anti-parallel" or "parallel"), combined vectorially to yield the resultant J, M.

The matrix element of a beta-emission can now be expressed as a sum of "matrix terms," each of which contains (besides nuclear functions) one function $\phi(JM, LS)$ and one of the Dirac operators of the chosen interaction.

Such a "matrix term" gives the probability of a transition in which the system $e+\nu$ is created in the state JM, LS, by the operator concerned. Inspection shows that the nonvanishing terms can be picked out, and each one classified with a "degree of forbiddenness" f (see Table I), by the following rules:

1. $S=0$ or 1 according to the operator (Table I, column 2).
2. For given J and S, $L=|J-S|$ to $J+S$ in integral steps.
3. $f=L$ for terms containing the operators 1, β, $\boldsymbol{\sigma}$, $\beta\boldsymbol{\sigma}$; while $f=L+1$ for $\boldsymbol{\alpha}$, $\beta\boldsymbol{\alpha}$, γ_5, $\beta\gamma_5$. Allowed transitions are denoted by $f=0$, first forbidden by $f=1$, etc.
4. If there is (is not) a nuclear parity change on emission, only terms with odd (even) f are nonvanishing.
5. If the nuclear spin change is $J_i\rightarrow J_f$, the possible values of J are $|J_i-J_f|$ to J_i+J_f in integral steps.

Thus from Table I, using rule 5 and selecting the Dirac operators of the chosen interaction, we can enumerate the f-values of all terms contributing to the beta-emission; the least f-value among

Table II. Degrees of forbiddenness f of transitions creating the system electron plus neutrino with total angular momentum J. For nuclear spin change $J_i\rightarrow J_f$, J ranges from $|J_i-J_f|$ to J_i+J_f. The degree of forbiddenness F of the emission as a whole is the least (even or odd) value of f in this range (for parity change no or yes, respectively). 0 = allowed. * = completely forbidden.

	$J=0$	1	2	3	4
Fermi ($1, \boldsymbol{\alpha}$)	$0, \underline{*}$	$\underline{1}, 2$	$2, \underline{3}$	$\underline{3}, 4$	$4, \underline{5}$
Tensor ($\beta\boldsymbol{\sigma}, \beta\boldsymbol{\alpha}$)	$2, \underline{1}$	$0, \underline{1}$	$\underline{1}, 2$	$2, \underline{3}$	$\underline{3}, 4$
Axial vector ($\boldsymbol{\sigma}, \gamma_5$)	$*, \underline{1}$	$0, \underline{1}$	$\underline{1}, 2$	$2, \underline{3}$	$\underline{3}, 4$